How Much Water Passes through the Indonesian Passages?

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LONG-TERM GOALS

The goal of this project was to obtain a more thorough understanding of the dynamics of the Indonesian Throughflow. We planned to establish new flow rate laws for currents forced through an arrangement of islands.

OBJECTIVES

We conducted analytical and numerical investigations of the Indonesian throughflow and made comparisons of the results with data collected as part of Arlindo II. ["Arlindo II" is a cooperative project of the U.S. and Indonesia. The abbreviation ARLINDO originates in Malay and stands for: avarus (sea), lintas (flow) and Indonesian.] In particular, we completed the examination of (1) the amount of water that can be forced through a single gap, and (2) the distribution of such flows through a "porous" wall containing a number of gaps. The interest focused on the application of the above calculations to warm (and fresh) Pacific waters exiting from the Indonesian Seas through the Lombok Strait, the Alor Strait and the Timor Passage.

The nature of my modeling work is that I simultaneously work on several projects; some of these projects are not necessarily closely related to each other. For this reason, some of the publications which are listed at the end of this report may appear to be somewhat disjointed.

WORK COMPLETED

Analysis of the throughflow's origin, and an analysis of the maximum flow rate that a broad gap on a beta-plane can handle.

RESULTS

Research has resulted in the preparation and publication of several papers, listed at the end of this report in the order that they were completed. Most have not been supported solely by ONR but also by NSF and NASA. The papers that are most closely related to the throughflow study are #1, #4 and #8. The most important aspect of these articles is the finding that all of the Indonesian throughflow must be upwelled into the thermocline somewhere along the equatorial Pacific.

In what follows I describe a detailed summary of the results (arranged in the order that the manuscripts have been completed during the past year).

The "separation formula," a new method for computing the inter-hemispheric meridional transport, was applied to the Pacific Ocean by integrating the equations of motion along the path shown in Figure 1 (paper #1). The model suggested that the observed Pacific to Indian throughflow is a measure of the upwelling (or cooling) in the Pacific. We then proposed a new theory for the generation of the Tsugaru and Alboran gyres (paper #2). The generation of these gyres is caused by the (otherwise imbalanced)
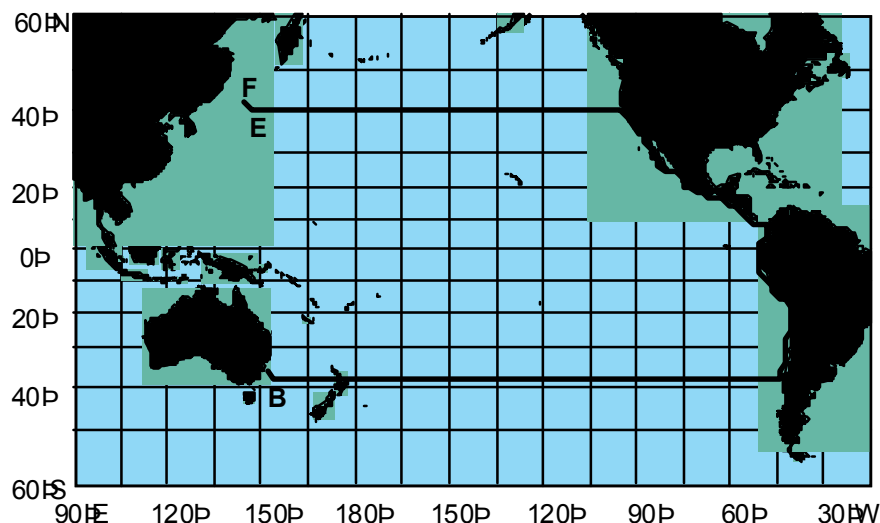
Figure 1.   The horseshoe integration path ABCDEF in the throughflow model study (paper #1). Sections AB and EF are perpendicular to the boundary currents, whereas BC and ED are zonal sections. The integration of the COAD wind stress was done in 2˚ squares.

flow force of the long-shore current downstream regardless of the initial current vorticity. Next, we applied a previously developed model describing the intimate relationship between retroflecting currents and the production of rings (Nof and Pichevin, 1996, *Journal of Physical Oceanography*, v. 26, 2344-2358) to the Agulhas Current (paper #3). We showed that the generation of rings from a retroflecting current in inevitable, and that there is no obvious relationship between the presence of so-called "Natal Pulses" and the production of rings.

The next study explored the nonlinear eastward propagation rate of the so-called Pacific warm pool, the region of high, sea-surface temperature associated with El Nino (paper #4). Typical values for the Pacific give a bounding propagation rate of 50–60 cm s^{-1} which is in good agreement with the observed migration rate during both the 1982-83 El Nino and the 1997 El Nino, the only ones in history that are known to result from an almost complete relaxation of the winds. Using a simple analytical model to compute the meridional warm water flux in the Atlantic (paper #5), we illustrated that a significant part of the water in the Global Conveyor Belt that ultimately sinks in the north Atlantic is of intermediate (cold) and not surface (warm) origin. The next study (paper #6) examined

the impingement of a westward drifting lens-like anticyclonic ring on a meridional boundary. We found that a ring encountering a wall stays roughly in a fixed latitude (rather than moving poleward), gradually leaking fluid toward the equator until it loses all of its mass. We concluded that rings such as warm-core Gulf Stream rings, Loop Current rings, Agulhas rings, as well as other eddies (e.g., Meddies) may behave in this fashion. Last, we examined the reason for the small transport within the Sea of Japan relative to that of the Caribbean and discovered that the reason for this difference is its relatively high latitude and not the size of the gaps connecting it to the Pacific Ocean (paper #7).

In paper #8, the established "island rule" and the recently introduced "separation formula" (see paper #1) were combined to yield an analytical expression for the total upwelling into the thermocline in the Pacific. Using analytics and numerics we were able to show that it is possible to compute the total upwelling into the thermocline in the Pacific from the difference between the transport given by the separation formula and the transport given by the island rule (provided that friction in the Indonesian Seas is ignored). Next, we focused on a way to examine the meridional flux of warm and intermediate water from the Southern Ocean into the South Atlantic by employing an integration of the linearized momentum equations along a closed contour containing the Americas, Greenland, the Atlantic and parts of the Arctic Ocean (paper #9). We found that the transport of the meridional overturning cell can be estimated from the wind field, the observed position of the North Atlantic Deep Water formation, and the observation that, although the Bering Strait allows the pressure across it to be continuous, there is no flow through it. We plan in future studies to examine these results with more detail using both observations and more general numerical simulations. Our research to date has culminated with a parallel study (paper #10) focusing on the meridional overturning cell in the Indian and Pacific Oceans. We found that in this case, the Indian and Pacific circulation cell is suppressed in the sense that it does not occupy the entire water column but rather is confined to a fraction of the column. We questioned the traditional assumption that the "great global conveyor" is driven primarily by thermohaline processes with the wind playing a secondary role. Instead, we were able to demonstrate that it is the wind field, not thermohaline processes, that is the main agent controlling the conveyor's transport.

IMPACT/APPLICATIONS

The results of our calculations for the single gap problem are formulas relating the transport through the gap to its width, latitude, depth and the sea-level difference between the connecting basins. Similarly, the multiple gap problem will yield formulas relating the relative transport that passes through each of the passages (i.e., the percentage of the total transport that a given passage can handle) to the size of each gap, the size and location of the adjacent gaps and the sea-level difference between the connecting basins. This useful information will then be compared to the actual transport calculated from shallow pressure gauges which will be available by the time that the theory is completed. The combination of these two independent means of computation will enable us to better understand the dynamics of the throughflow. Without this combination it is doubtful that a thorough understanding can be achieved.

RELATED PROJECTS

This project is closely related to the NSF project # OCE-9503816 entitled "Flows through multiple gaps with applications to the Indonesian Throughflow." However, this NSF grant supports the study of the western rather than the eastern passages which are the focus of the ONR grant. Also, the NASA

project # NAG5-4813 entitled "Studies of Variable Climate Processes" (completed earlier this year) examined the exchange of surface water between the Indian and Pacific Oceans.

PUBLICATIONS

1. Nof, D., 1999: The 'separation formula' and its application to the Pacific Ocean. *Deep-Sea Research,* **45**, 2011-2033.

2. Nof, D. and T. Pichevin, 1999: The establishment of the Tsugaru and the Alboran gyres. *Journal of Physical Oceanography*, **29**, 39-54.

3. Pichevin, T., D. Nof and J. Lutjeharms, 1999: Why are there Agulhas rings? *Journal of Physical Oceanography*, **29**, 693-707.

4. Nof, D. and S. Van Gorder, 1999: Intense nonlinear migrations of the Pacific warm pool. *Deep-Sea Research I*, **46**, 1705-1731.

5. Nof, D. and S. Van Gorder, 1999: A different perspective on the export of water from the South Atlantic. *Journal of Physical Oceanography*, **29**, 2285-2302.

6. Nof, D., 1999: Strange encounters of eddies with walls. *Journal of Marine Research,* in press.

7. Nof, D., 1999: Why much of the circulation in the Atlantic enters the Caribbean Sea and very little of the Pacific circulation enters the Sea of Japan. *Progress in Oceanography,* in press.

8. Nof, D. and S. Van Gorder, 1999: Upwelling into the thermocline in the Pacific Ocean.   *Deep-Sea Res.,* revised and resubmitted.

9. Nof, D., 1999: The import and export of upper and deep water by the South Atlantic. *J. Phys. Oceanogr.,* revised and resubmitted.

10. Nof, D., 1999: Is there a meridional overturning cell in the Pacific and Indian Oceans? *Science*, submitted.